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SUMMARY REPORT OF VALVELESS PULSEJET INVESTIGATIONS ON THE C.A.L. 10-FOOT WHIRLING ARM

MARCH 1957

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TABLE OF CONTENTS

ABSTRACT

This report summarizes the preliminary tests of valveless pulsejet engines for application as helicopter tip mounted power plants. These tests were conducted from September 1954 to March 1957 with 4-inch diameter and $5\frac{1}{2}$-inch diameter engines on the Cornell Aeronautical Laboratory 10-foot rotor whirling arm test stand at tip speeds up to 600 fps. Major emphasis has been placed upon evaluating the effect of exhaust to inlet area ratio and fuel injection system upon engine performance and stability over the test speed range.

These tests have indicated that stable resonant operation could be sustained throughout the 0-600 fps tip speed range. Available thrusts of up to 21 lbs. have been obtained with the $5\frac{1}{2}$-inch diameter engine with thrust specific fuel consumptions somewhat less than 7 lbs. fuel per hour per pound thrust at 600 fps tip speed.

INTRODUCTION

The possibility of employing the valveless pulsejet as a tip-mounted helicopter rotor drive has in recent years been the subject of investigation at Cornell Aeronautical Laboratory. In general, this type of power plant can be characterized by simplicity of design, ease of construction, high thrust per unit weight and relatively low specific fuel consumption. Although other jet propulsion power plants such as the conventional pulsejet and the ramjet which exhibit the same general characteristics have been considered as propulsion units, the optimum speed range for the application of each type of propulsion unit is different, Fig. 1. The optimum speed range for the conventional pulsejet is the low speed range, 0-400 fps, whereas the optimum speed range for the ramjet is at high subsonic and supersonic speeds $M = 0.9$ and upwards. In contrast, the valveless pulsejet has comparatively constant performance over the subsonic speed range.

The development of the valveless pulsejet has been undertaken by C.A.L. originally under Project SQUID (Ref. 1 and 2) and later under a more comprehensive contract awarded by the Office of Naval Research to develop a power plant for the 400-600 fps speed range for application to various Navy requirements including helicopters and missiles.

The valveless pulsejet operates on an intermittent cycle sustained without the use of inlet flapper valves. Early development at C.A.L. had indicated that valveless pulsejet engines could be made to operate either statically or under ram conditions depending on the exhaust nozzle configuration. It was found experimentally that for static operation a divergent exhaust nozzle was necessary for resonant operation, whereas for high speed ram operation a convergent exhaust nozzle was necessary, Fig. 2. In addition, in order to improve the aerodynamics of the ram-air-operating pulsejet and in order to utilize the ram pressure most efficiently the side inlet used on the static operating engine was replaced by a nose inlet.

In order to evaluate the potential of the valveless pulsejet for missile application, a 14-inch diameter engine was developed and tested in the Induction Tunnel Air Blast Facility of the Naval Air Missile Test Center at Pt. Mugu, California (Ref. 3). These tests indicated that at a Mach number of $M = 0.65$ the thrust specific fuel consumption was 5.3 lb. fuel per hour per lb. thrust with an available specific thrust of approximately 1.7 lb. per sq. in. Although these tests showed considerable promise, further development of this engine for missile application was suspended in favor of the development of the valveless pulsejet for a helicopter tip mounted power plant.

TEST PROGRAM AND RESULTS

Whirling arm tests of early C.A.L. valveless pulsejet configurations have been conducted in recent years at the Chesapeake Bay Annex of the Naval Research Laboratory, and a summary of these tests may be found in Ref. 4. However, the evaluation and development of the improved valveless pulsejet configurations for the helicopter application necessitated the construction at C.A.L. of a whirling arm test facility, in order to subject the engine to actual flight conditions. This facility, Fig. 3, uses a 180 hp Chrysler industrial gasoline engine to drive a counterbalanced symmetrical NACA 0015 airfoil with a 10-ft. span and 18-inch chord at tip speeds up to 700 fps. The engine drives the rotor through a fluid clutch, a Falk 6.15 to 1 gear ratio right angle speed reducer and a Baldwin SR-4 strain gage type torquemeter capable of measuring torques up to 30,000 inch pounds. All other instrumentation, such as fuel supply and ignition, is carried to the test engine by overhead lines to either a rotary coupling or slip rings as required and along the rotor spar to the tip. The available thrust is determined by measuring the difference between the power required to drive the rotor alone at a given speed with the engine detached and the power required to drive the rotor with the test engine in operation at the same speed. The measured decrease in necessary driving power represents the usable power input of the test engine into the drive shaft.

The initial valveless pulsejet engine, Fig. 4, designed to be tested on this test facility was a scaled-down version of the 14-inch diameter engine used in the induction tunnel tests at Pt. Mugu. A combustion chamber diameter of 4 inches was selected based on the specific available thrust obtained in the tunnel tests. During the shakedown-test phase no attempt was made to obtain a clean aerodynamic engine configuration, and therefore the first test results showing up to 10 lbs. gross thrust at 500 fps were not especially significant. (The gross thrust value represents the difference between the measured arm drag with the valveless pulse jet engine installed and not operating, and the arm drag with the engine in operation.) However, these early tests yielded the important observation that the range of resonant operation was controllable by changes in exhaust area, i.e., a reduction in exhaust area was accompanied by an increase in the speed range of resonant operation. On the other hand, tests directed to determine the effect of restricting the air inlet indicated that reduction in inlet area adversely affected the speed range in which resonant operation could be sustained. In order to obtain an indication of the operating frequency of the 4-inch diameter valveless pulsejet, the stroboscopic effect obtained by synchronizing the rotor speed and the pulsejet frequency was utilized. Photographs of the engine in operation were taken at night of the essentially stationary pulses obtained with the above-mentioned scheme. At 300 fps, the frequency of engine operation was of the order of 80 cycles per second. Fig. 5 is a composite photograph showing the ring of flame resulting from a time exposure at night at about 300 fps tip speed.

Drag calibrations were undertaken in order to determine the drag contributions of the various components of the test facility. These tests indicated that the drag of the jet mounting bracket, Fig. 4, contributed a large portion of the total arm drag. In order to lower the drive power requirements and to increase the maximum tip speeds available for testing, a streamlined housing was fabricated for the mounting bracket, Fig. 6. The power required to drive the arm and streamlined mounting bracket is shown in Fig. 7.

Performance evaluation tests conducted with the 4-inch diameter valveless pulsejet indicated that the available thrust developed was approximately equal to the difference between the drag of the rotor and jet mounting bracket and the drag of the system with the jet in operation as determined from the torquemeter measurements. The small observed available thrust indicated only that the valveless pulsejet produced positive thrust over the test speed range. In view of the small jet output as compared with the large power requirements of the rotor, a $5\frac{1}{2}$-inch diameter engine was designed with the same over-all length in order to obtain a proportionally greater contribution of jet drive power. Meanwhile performance tests with the 4-inch diameter pulsejet designed to explore the effect of variation in exhaust nozzle area upon the measured available thrust were completed.

These performance tests were conducted with an engine inlet of 1-1/8-inch diameter and the exhaust area was varied in small increments from 1-1/8 inch to 1-7/8 inch in diameter in the 250 to 500 fps tip speed range. The results of these tests are summarized in Table 1, where the values shown are the difference in torquemeter measurements with the hot and cold engine and as such represent a measurement of gross thrust. In these tests the maximum gross thrust values were obtained with an exhaust diameter of 1-7/8 inch (an exhaust to inlet area ratio of 1.86).

Upon completion of the $5\frac{1}{2}$-inch diameter valveless pulsejet, Fig. 11A, testing with the smaller diameter engine was suspended. Drag calibrations were again undertaken to determine the contribution of the enlarged valveless pulsejet and that of the rotor blade and mounting bracket, Fig. 8. A test program was designed to investigate systematically the effects of exhaust to inlet area ratios, inlet diffuser geometry and fuel injection configuration upon engine performance. Engine area ratios of 1.0, 1.1, 1.2, 1.3, 1.4, and 1.6 were tested and fuel injectors of 2, 4, 6, $7\frac{1}{2}$, $10\frac{1}{2}$, and 12 gph capacity were evaluated at each area ratio.

TIP SPEED	EXHAUST DIA					
FPS	1 1/8	1 5/16	1 1/2	1/5/8	1 3/4	1 7/8
GROSS THRUST *						
250	2.7	2.7	2.7	2.7	2.7	3.6
300	1.8	3.6	3.6	3.6	3.6	3.6
350	1.8	3.6	3.6	4.5	3.6	4.5
400	1.8	5.4	4.5	4.5	5.4	5.4
450	1.8	5.4	3.6	7.2	4.5	6.3
500		2.7	4.5	5.4	5.4	7.2

Table I

4" DIA VALVE PULSEJET PERFORMANCE

*Uncorrected for jet drag.

With the initial inlet diffuser employed, Fig. 11A, the tests indicated that with exhaust to inlet area ratios in excess of 1.2, resonant operation of the valveless pulsejet could not be sustained throughout the available test speed range. For an exhaust to inlet area ratio of 1.1, Fig. 9 shows the performance of the pulsejet with various capacity fuel injectors. For the same $5\frac{1}{2}$-inch diameter engine with an area ratio of 1.1 and with a 6 gph capacity fuel injector, Fig. 10 indicates the effect of increasing fuel consumption on maximum available thrust at a tip speed of 400 fps. With an exhaust to inlet area ratio of 1.2, similar tests up to 500 fps indicated no significant changes in performance. However, at maximum tip speeds evidence of fuel puddling became apparent in the form of a raw fuel discharge from the outboard side of the exhaust nozzle. These tests are summarized in Table 2, in which the minimum observed specific fuel consumption based on available thrust was somewhat less than 10 lbs. per hour per lb. thrust. Since the increased fuel injection pressure obtained as a result of the high centrifugal field at the higher tip speeds resulted in increased fuel flow and apparent puddling, small capacity fuel injectors were employed in an effort to reduce this high speed effect. However, with fuel injectors of 0.8, 1.0, and 2.0 gph capacity, it was found that at low speeds the restricted fuel orifices, together with the low fuel injection pressures, resulted in too lean a fuel-air mixture for ignition. On the other hand, at the higher tip speeds the increased flow velocity through the combustion region made ignition more difficult.

In view of the magnitude of the fuel injection problem, a concurrent test program was initiated to develop an improved fuel-injection system

FUEL NOZZLE GPH	TIP SPEED FPS	AVAILABLE* THRUST LB	FUEL LB/HR	SFC $\frac{LB/HR}{LB}$
2	268	1.8	84	46.6
2	315	1.8	88	48.9
2	343	4.5	88	19.5
2	365	4.5	92	20.4
2	382	6.3	92	14.6
2	404	6.3	98	15.6
2	428	4.5	98	21.8
2	450	6.3	98	15.6
2	480	9.9	100	10.1
2	498	9.9	96	9.7
4	211	4.5	64	14.2
4	242	5.4	72	13.3
4	281	4.5	76	16.9
4	307	4.5	80	17.8
4	337	8.1	84	10.4
4	358	10.8	90	8.3
4	384	7.2	88	12.2
4	402	7.2	88	12.2
4	428	7.2	90	12.5
4	466	9.0	90	10.0
4	493	9.9	94	9.5
6	292	1.8	86	47.8
6	309	3.6	90	25.0
6	341	7.2	94	13.1
6	358	6.3	96	15.2
6	378	4.5	96	21.4
6	402	6.3	100	15.9
6	435	7.2	100	13.9
6	452	7.2	96	13.3
6	473	9.0	98	10.9
6	497	9.9	100	10.1
7.5	275	1.8	88	40.9
7.5	306	3.6	88	24.4
7.5	345	5.4	92	17.0
7.5	372	5.4	96	17.8
7.5	400	7.2	96	13.3
7.5	419	6.3	94	14.9
7.5	450	7.2	96	13.3
7.5	475	9.9	96	9.7
7.5	496	9.0	104	11.6

C

Table 2

SUMMARY OF PERFORMANCE OF $5\frac{1}{2}$" DIA VALVE PULSEJET

* Based on measured torque with the engine operating less the measured arm torque with the engine removed.

using the C.A.L. Allison engine powered free-air blast test facility. While it is apparent that these tests would not be indicative of the whirling performance of an engine with the test fuel injection system, they would be indicative of the relative merits of each fuel system tested under the same flow velocity. Free air blast tests with the valveless pulsejet indicated that fuel injection rings with several small injection orifices were superior to the conventional Monarch fuel nozzles used. Performance evaluations of the fuel ring on the whirling arm pulsejet failed to yield any correlation with the free air blast tests concerning the superiority of the types of fuel injectors. However, in comparing the whirling arm engine and that used in the free air blast tests, it was noted that the free air blast engine had a 3-inch exhaust diameter whereas the engine used in whirling arm tests had a 2-5/8-inch exhaust diameter. The whirling arm engine was removed for a suitable modification in exhaust area, meanwhile, drag calibrations were undertaken in order to extend the maximum test speed range to 600 fps.

In the higher tip speed range, tests of the $5\frac{1}{2}$-inch diameter valveless pulsejet were carried out using area ratios of 1.1 and 1.2. Each of these configurations was again tested with a range of Monarch fuel injectors. Resonant operation over the entire 0-600 fps tip speed range could be sustained only with the 4 and 6 gph capacity injectors; with the larger nozzles, resonant operation could not be sustained above tip speeds of approximately 400 fps. Although resonant operation over the full speed range could be sustained with the smaller capacity injectors, little or no available thrust was indicated. With an area ratio of 1.2 and a 4 gph fuel injector, available thrusts of 5 lbs. were obtained at tip speeds of 600 fps.

In view of the difficulties encountered in pulsejet ignition with small injectors at low tip speeds and in view of flame blow out at the higher speeds, a new inlet diffuser was designed so as to allow rapid expansion of the ram air as close to the engine inlet as possible. It was felt that the new diffuser would result in lower combustion chamber flow velocities and an improved ram air distribution in the combustion regions as well as effectively increasing the time available for fuel-air mixing prior to ignition. In addition, the exhaust nozzle was replaced with a streamlined nozzle in order to improve the external flow over the tailpipe. The initial tests with the valveless pulsejet with these modifications, Fig. 11B, indicated a considerable reduction in the thrust loss due to high external drag, Fig. 12. With an exhaust to inlet area ratio of 1.0, these tests indicated that it was possible to sustain resonant operation throughout the entire 0-600 fps speed range with 2, 4, 6, 7½, 10½, and 12 gph capacity fuel injectors. In addition, available thrust of 7 lbs. were obtained even with the small exhaust area tested.

In view of the improved thrusts resulting from these modifications, a test program was carried out to evaluate the performance at area ratios of 1.1, 1.2, 1.3, and 1.45 (exhaust diameters of 2-5/8, 2-3/4, 2-7/8, and 3 ins.). For each of these area ratios a range of fuel injectors of 2, 4, 6, and 7½ gph capacity were used. It was possible to sustain resonant operation throughout the entire 0-600 fps speed range with all the configurations tested.

The effect of exhaust diameter upon the maximum available thrust for these tests with the $5\frac{1}{2}$-inch diameter engine with a 6.0 gph fuel injector is shown in Fig. 13 for tip speeds of 500 and 600 fps. From this figure it can be seen that maximum available thrust is obtained with an engine exhaust diameter of 2-5/8 inches (area ratio = 1.1). The effect of fuel injector capacity upon the specific fuel consumption of this engine for an area ratio of 1.0 is shown in Fig. 14. For the 2 gph injector, the specific fuel consumption is observed to be approximately constant throughout the test speed range, as would be expected for the valveless pulsejet engine. In these tests available thrusts of about 7 lbs. were obtained at 600 fps. The increase in fuel injector capacity from 2 to 4 gph produced an increase in specific fuel consumption. In general, the maximum available thrusts were not achieved at the minimum specific fuel consumption values. Available thrusts of about 10 lbs. were obtained using a 6.0 gph injector, Fig. 13, with a corresponding specific fuel consumption of about 14 lb. fuel per hour per lb. thrust at 600 fps. Individual maximum available thrusts with this engine configuration have been as high as 13 lbs.

Since the optimum exhaust to inlet area ratio for the 5-1/2 inch diameter valveless pulsejet, for maximum thrust, appeared to be about 1.1, studies were carried out to improve the fuel injection system with this configuration. In order to improve fuel atomization as well as to provide longer times in which to accomplish complete combustion, the location of the fuel injector was varied. These tests indicated that with the fuel injector located about 4 inches from the engine inlet, improvements in the available thrust of up to 2 lbs. could be achieved at the higher tip speeds.

In order to further improve the fuel distribution in the combustion chamber, fuel rings were fabricated and tested. These fuel rings had a series of holes along the periphery and a total fuel flow of about 6 gph. The individual fuel jets from the periphery of the ring covered the complete range from axial to radial injection. The preliminary tests indicated that the radial fuel injection yielded the maximum pulsejet thrusts, in excess of 15 lbs. available thrust at 600 fps tip speed. Although the use of the fuel injection rings resulted in improved thrust, fuel flow control was more difficult and no improvement in specific fuel consumption was noted. The minimum thrust specific fuel consumption values observed were between 10 to 13 lb. fuel per hour per lb. thrust at 600 fps.

In conjunction with these fuel injector modifications, turbulators were installed in the test engine in order to explore the effect of increased turbulence upon engine burning and performance. The first of these turbulators was a perforated annular ring aligned parallel to the jet axis enclosing the spark plug. The net effect of this device was to significantly reduce blowout at the higher tip speeds and to permit easy ignition over the entire speed range. Maximum thrusts, using fuel rings, of up to 14 lbs. were obtained with no significant reduction in specific fuel consumption. A vane type turbulator to swirl the air fuel mixture prior to ignition was also tested. The tests with this turbulator indicated available thrusts of up to 12 lbs. with optimum specific fuel consumption of about 10 lb./hr./lb. However, considerable difficulty was experienced in starting the engine and in maintaining resonant operation.

Since the increase in turbulence level in the combustion chamber of the valveless pulsejet did not indicate any apparent improvement in engine performance, all further tests were conducted without turbulators. A summary of these tests for both the fuel ring and fuel nozzle configurations is shown in Table 3. Although the available thrust output using fuel rings was observed to be better than the results using nozzles, little or no improvement in thrust specific fuel consumption was observed. Figures 15 and 16 show the general performance of the valveless pulsejet with the two types of fuel injectors. For simplicity individual data points have been eliminated and only the average performance range indicated. The corresponding performance of the Hiller 2B150 ramjet[5] at zero degrees pitch has been included. However, since the performance of this ramjet is dependent upon the pitch angle as well as tip speed, the optimum performance is also presented.

The available specific thrust of the valveless pulsejet at zero degrees pitch is superior to the equivalent ramjet regardless of fuel injector configuration. The ring type fuel injector yields results superior in specific thrust than those reported for the best Hiller 2B150 ramjet performance at optimum pitch angle. Similarly, the thrust specific fuel consumption of the valveless pulsejet was observed to be superior to that obtained with the Hiller 2B150 ramjet at the same pitch angle. Although the optimum specific fuel consumption of the ramjet falls within the range obtained with the pulsejet, the pulsejet continues to exhibit the lowest specific fuel consumptions.

FUEL NOZZLE	TIP SPEED	AVAILABLE THRUST	SPECIFIC FUEL CONSUMPTION
GPH	FPS	LB	LB/HR/LB
4	300	2.7	18.5
4	350	2.7	13.3
4	410	5.4	16.6
4	455	5.9	13.7
4	496	6.8	17.2
4	550	9.0	15.1
4	600	10.8	12.8
6	350	5.0	24.0
6	400	6.7	19.0
6	450	8.0	17.0
6	500	10.0	15.1
6	550	11.1	12.1
6	600	13.4	10.5
10	350	5.0	22.0
10	400	6.2	16.1
10	450	6.4	14.1
10	500	9.3	13.0
10	550	9.4	11.8
10	600	12.9	10.1
12	400	6.6	15.2
12	450	8.0	14.9
12	500	8.8	13.6
12	550	11.9	11.9
12	600	13.3	10.5
15	400	6.4	20.0
15	450	7.2	19.4
15	500	8.8	14.7
15	550	9.2	13.1
15	600	12.9	9.4

TIP SPEED	AVAILABLE THRUST	SPECIFIC* FUEL CONSUMPTION
FPS	LB	LB/HR/LB
300	5.0	14.9
300	9.5	13.8
350	6.1	11.1
400	7.5	16.0
400	8.8	11.4
430	9.5	12.3
450	8.6	17.1
450	10.5	12.3
475	11.5	11.3
475	13.4	10.6
500	13.6	14.7
500	12.7	11.7
500	12.8	11.0
500	13.5	8.9
500	13.9	8.7
550	16.0	9.6
550	16.0	7.6
600	17.3	10.1
600	21.0	10.0
600	20.0	9.8
600	17.8	8.9
600	18.4	7.6
600	18.0	6.7

*FUEL RINGS USED

TABLE 3

PERFORMANCE SUMMARY FOR 5½" DIAMETER VALVELESS PULSEJET
WITH AN EXHAUST TO INLET AREA RATIO OF 1.1

SUMMARY

The tests of the valveless pulsejet engine on the C.A.L. whirling arm test stand have indicated that lower thrust specific fuel consumption values based on available thrust can be achieved with these engines than with present day ramjets in the 400 to 600 fps speed range.

It was possible to sustain stable resonant operation with the improved valveless pulsejet configurations up to speeds of 600 fps. No ignition difficulties were encountered. Major improvements in performance were obtained as a result of external streamlining, the use of proper exhaust to inlet area ratios and improved fuel injection systems.

The engine configuration yielding maximum performance consisted of a 5-1/2 inch diameter combustion chamber, a 2-1/2 inch diameter inlet, a 2-5/8 inch exhaust diameter and a ring-type fuel injector. This engine exhibited an available specific thrust of 0.8 lb./sq. inch and a minimum thrust specific fuel consumption of 7 lbs. fuel/hr./lb. thrust at 600 fps.

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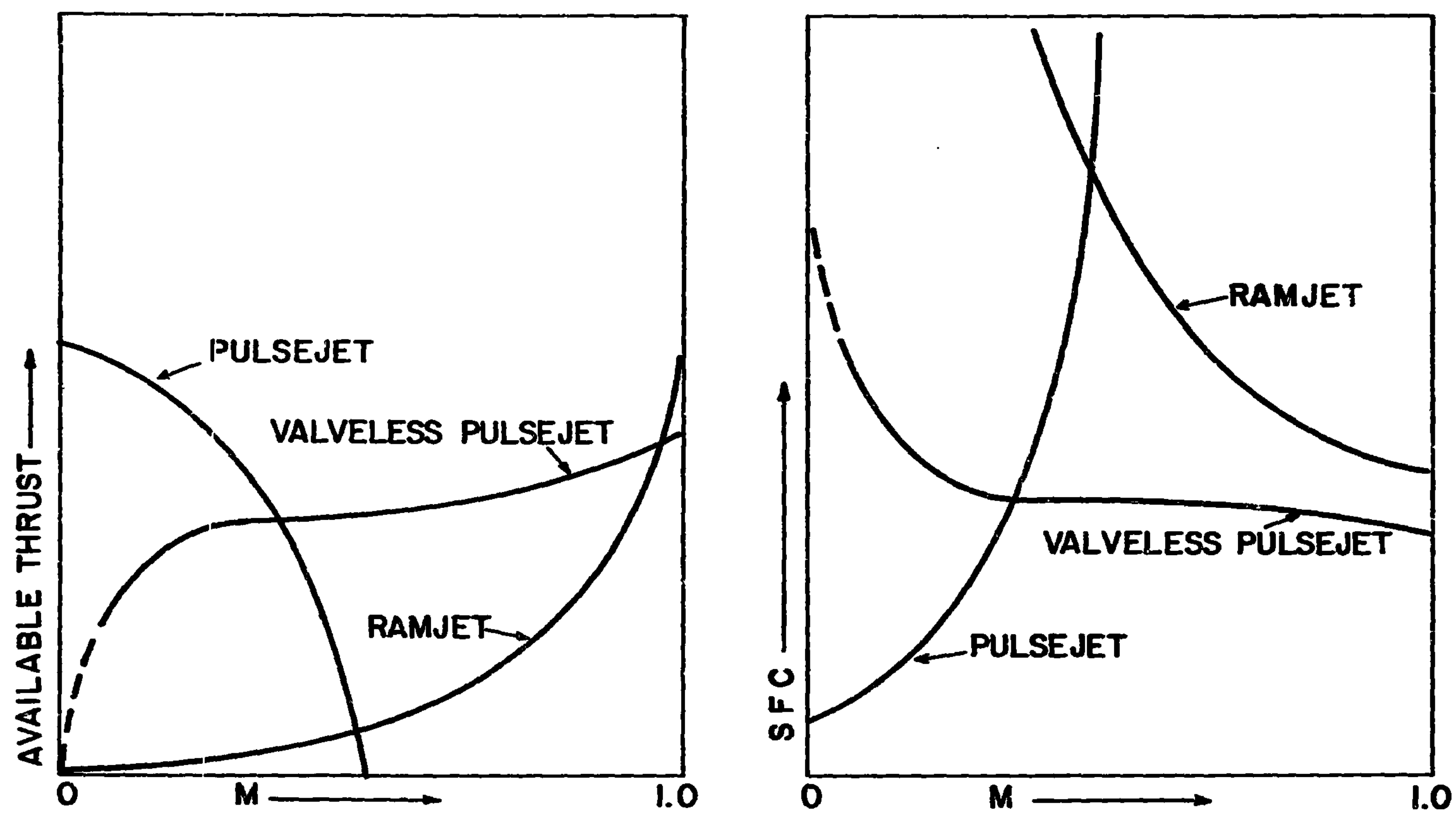

Figure I
OPTIMUM SPEED RANGES FOR POSSIBLE TIP MOUNTED POWERPLANTS

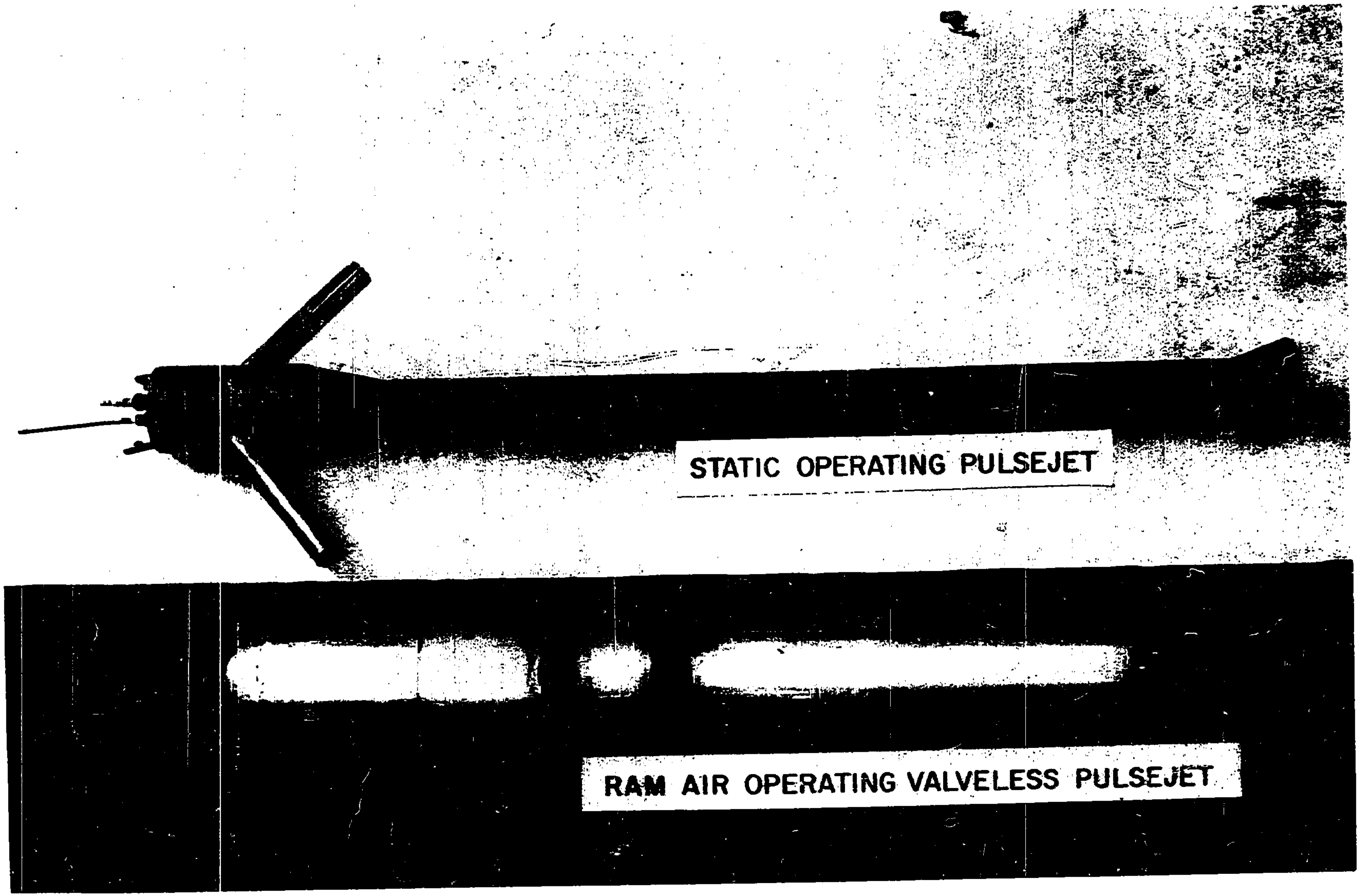

Figure 2
STATIC & RAM AIR OPERATING VALVELESS PULSEJETS

Figure 3
WHIRLING ARM TEST STAND

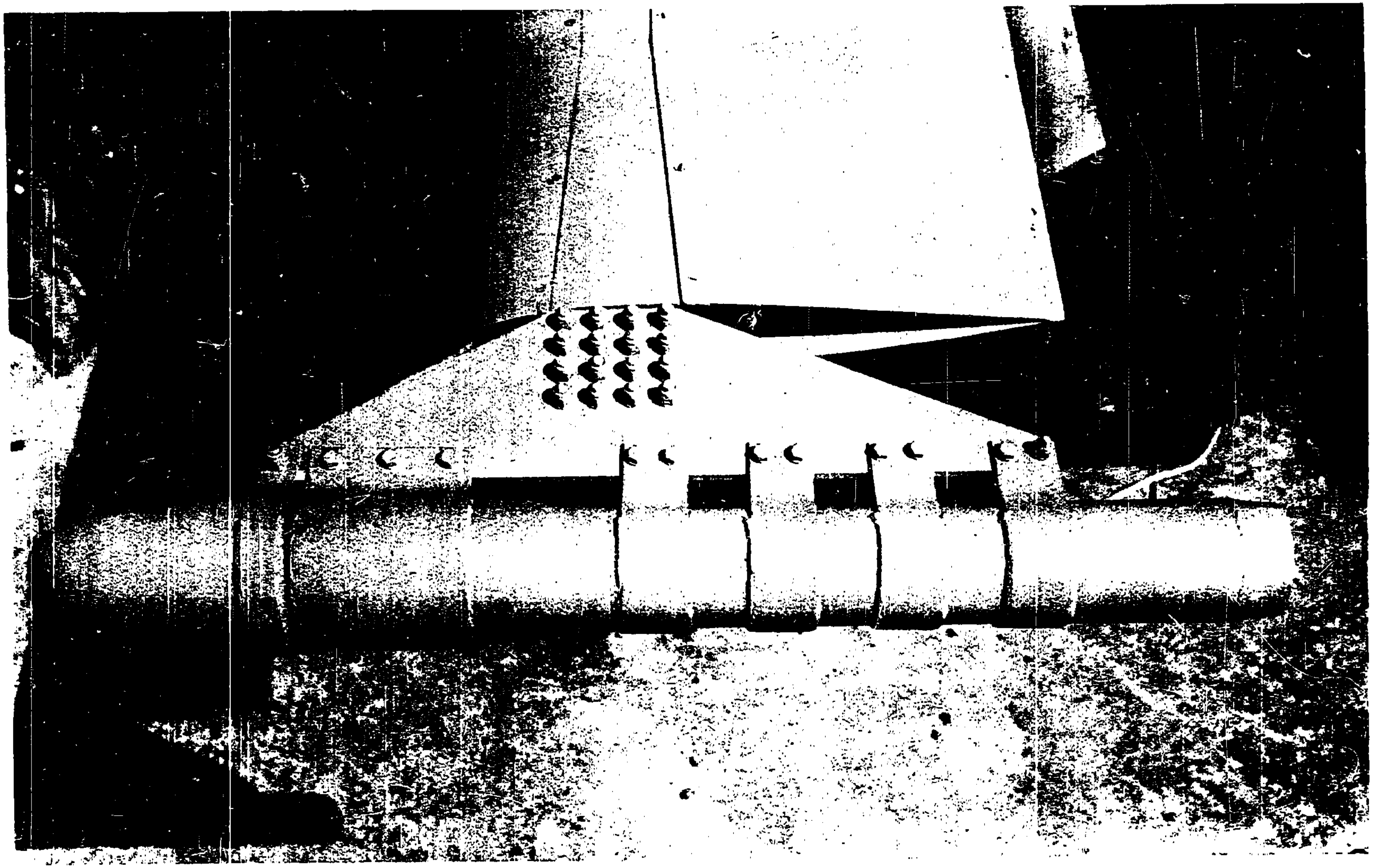

Figure 4

4" DIA. VALVELESS PULSEJET & MOUNTING BRACKETS

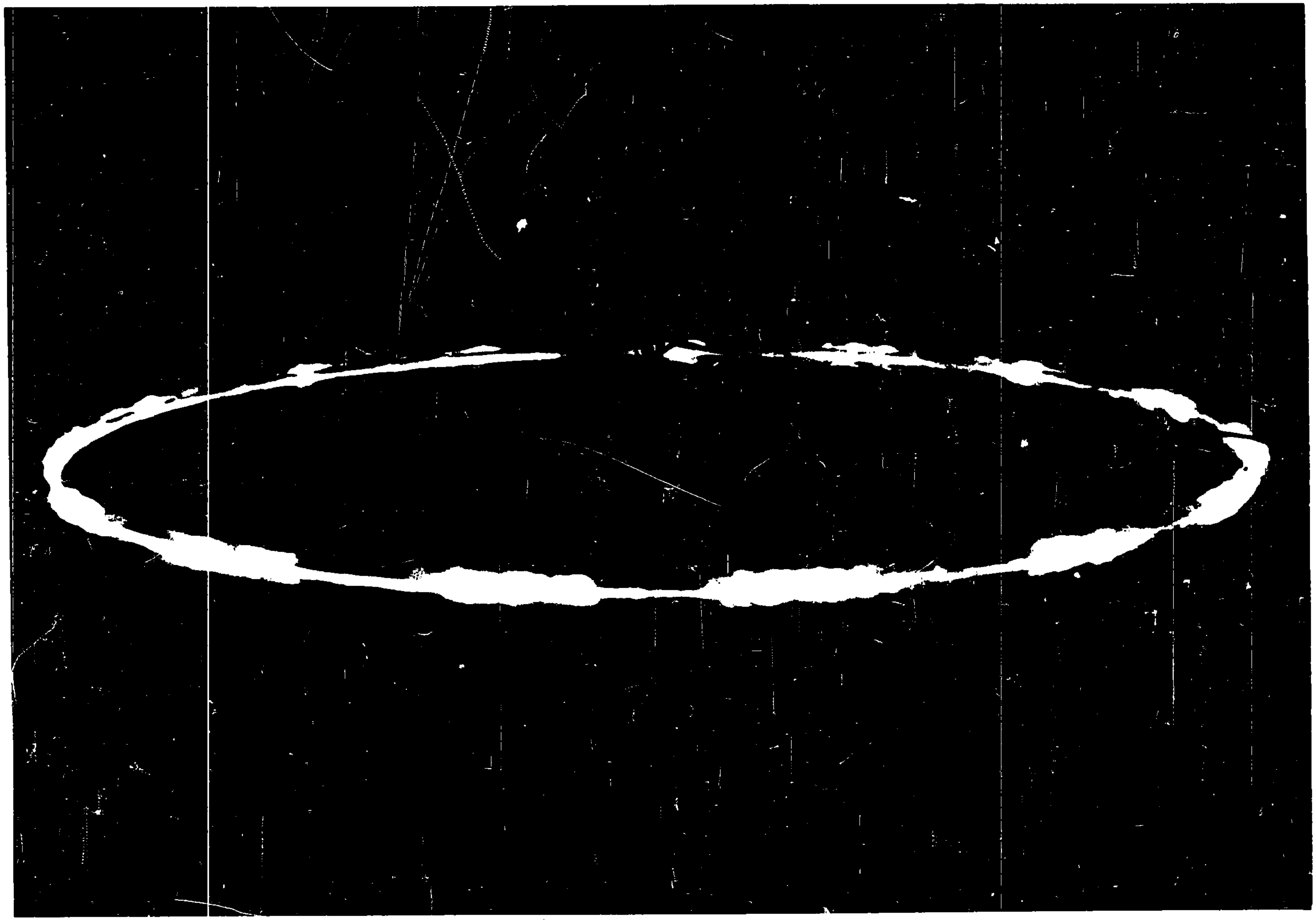

Figure 5

VALVELESS PULSEJET OPERATION

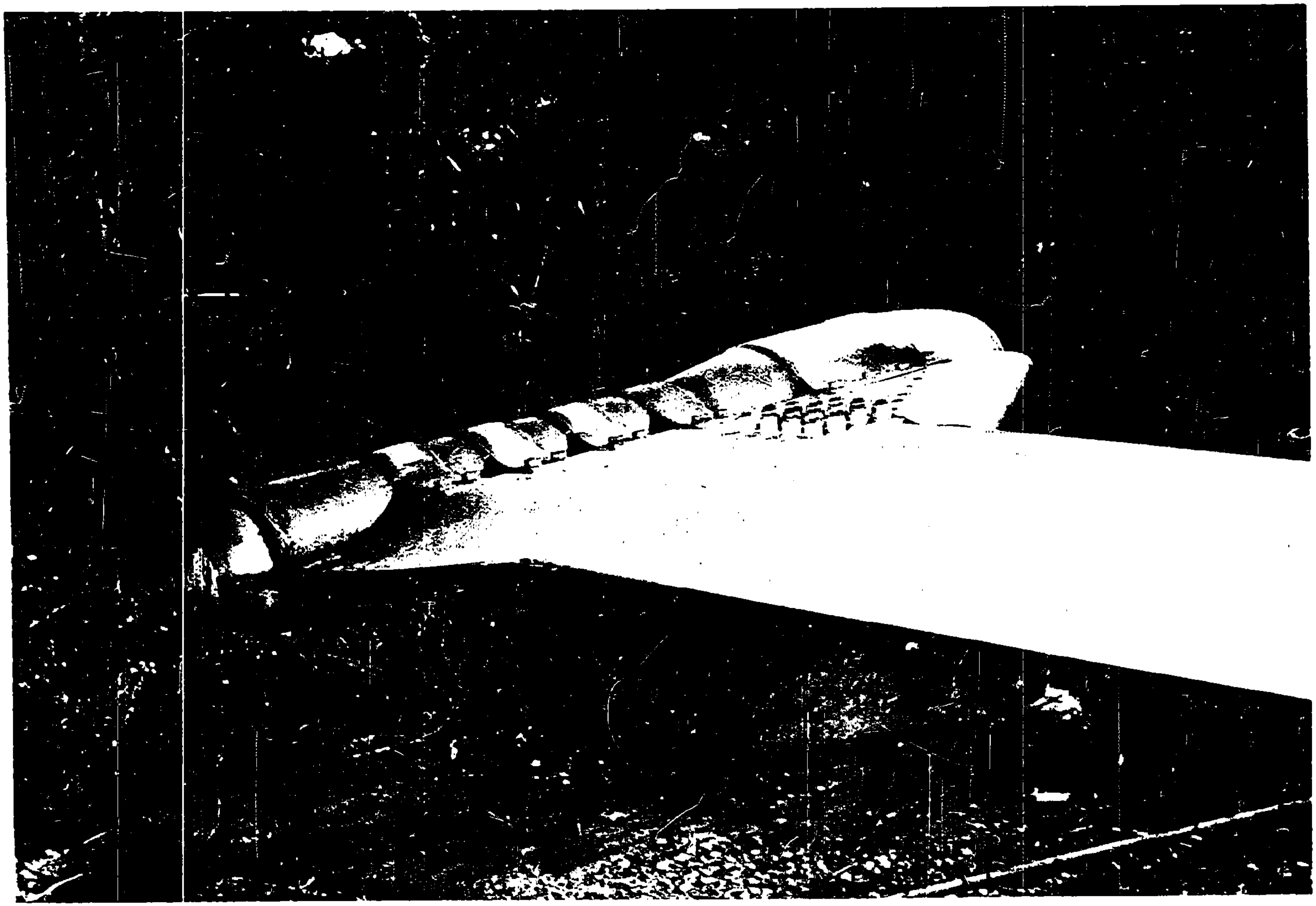

Figure 6

5 1/2" DIA. VALVELESS PULSEJET & STREAMLINED MOUNTING BRACKETS

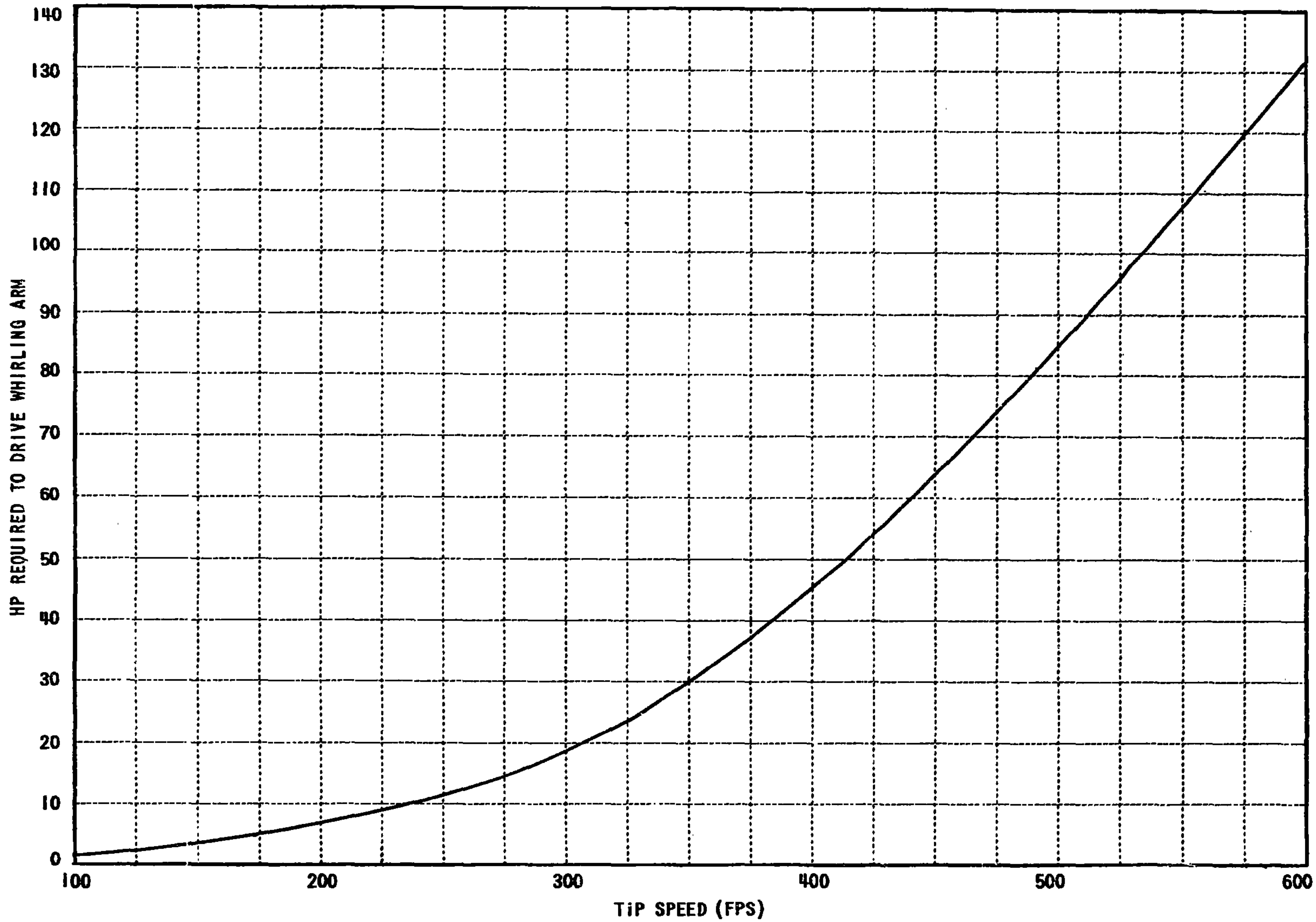

Figure 7
POWER REQUIRED TO DRIVE WHIRLING ARM

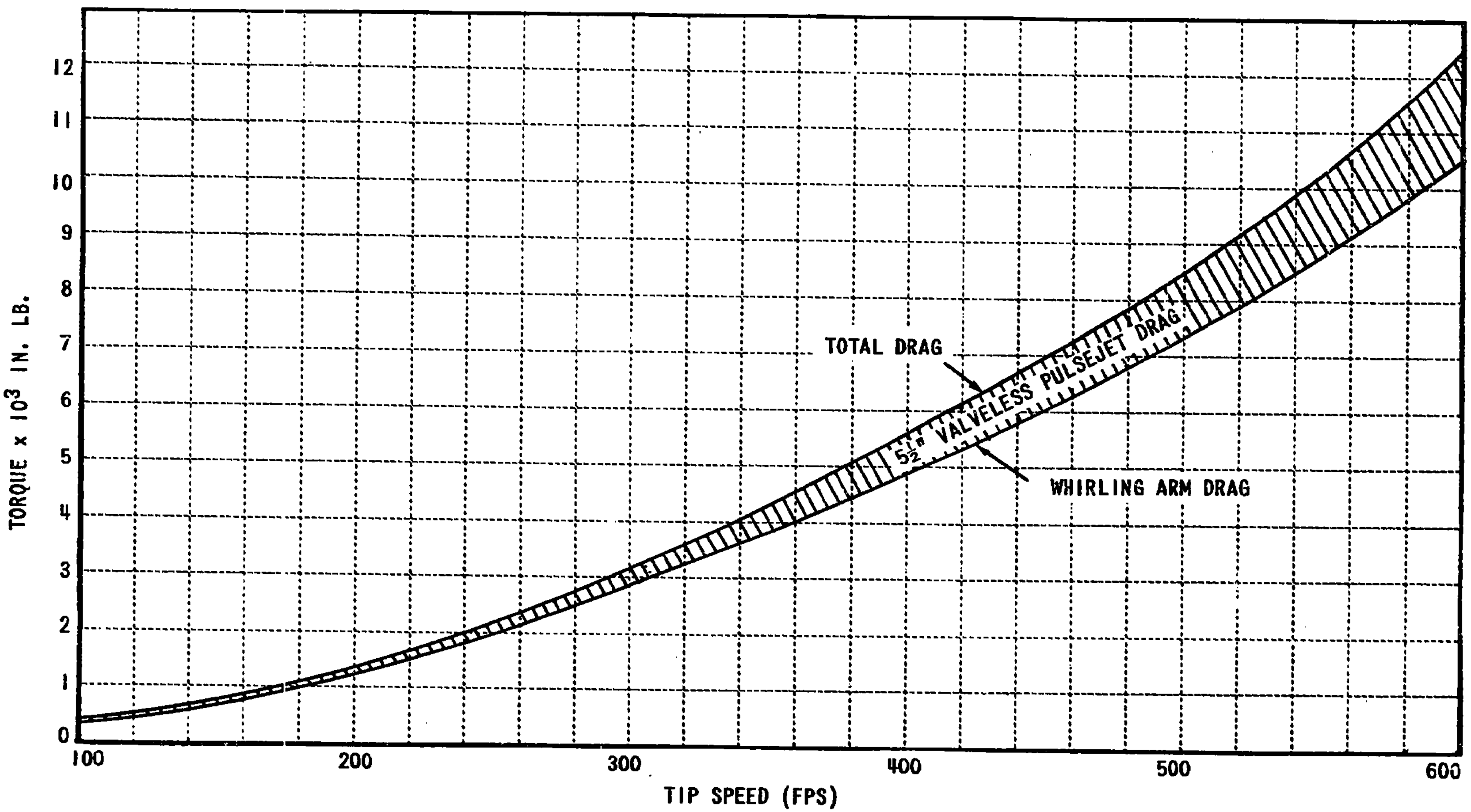

Figure 8

5½" DIA VALVELESS PULSEJET DRAG

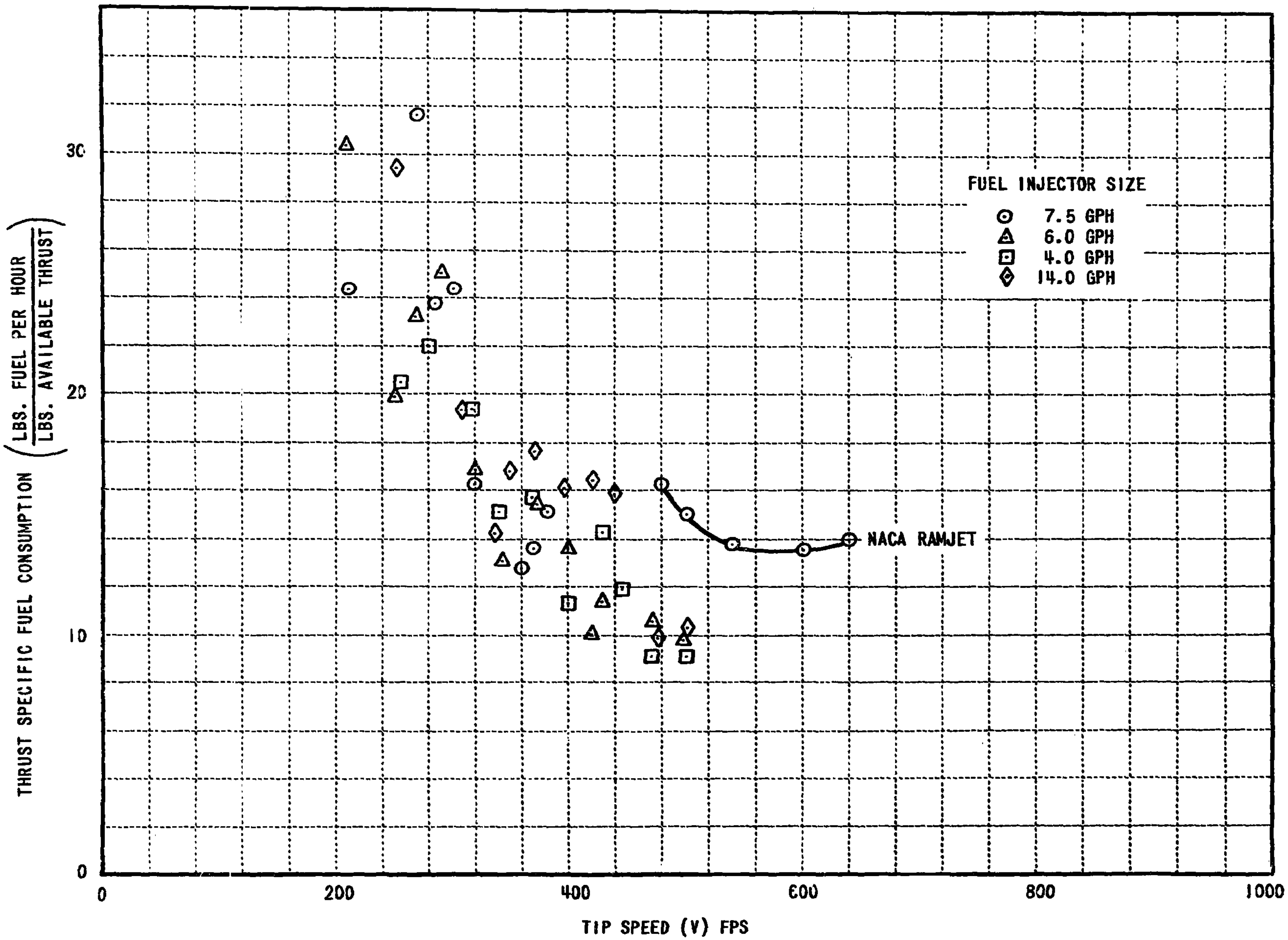

Figure 9

EFFECT OF FUEL INJECTOR CAPACITY UPON PERFORMANCE OF $5\frac{1}{2}$" DIA VALVELESS PULSE JET AREA RATIO - 1.1

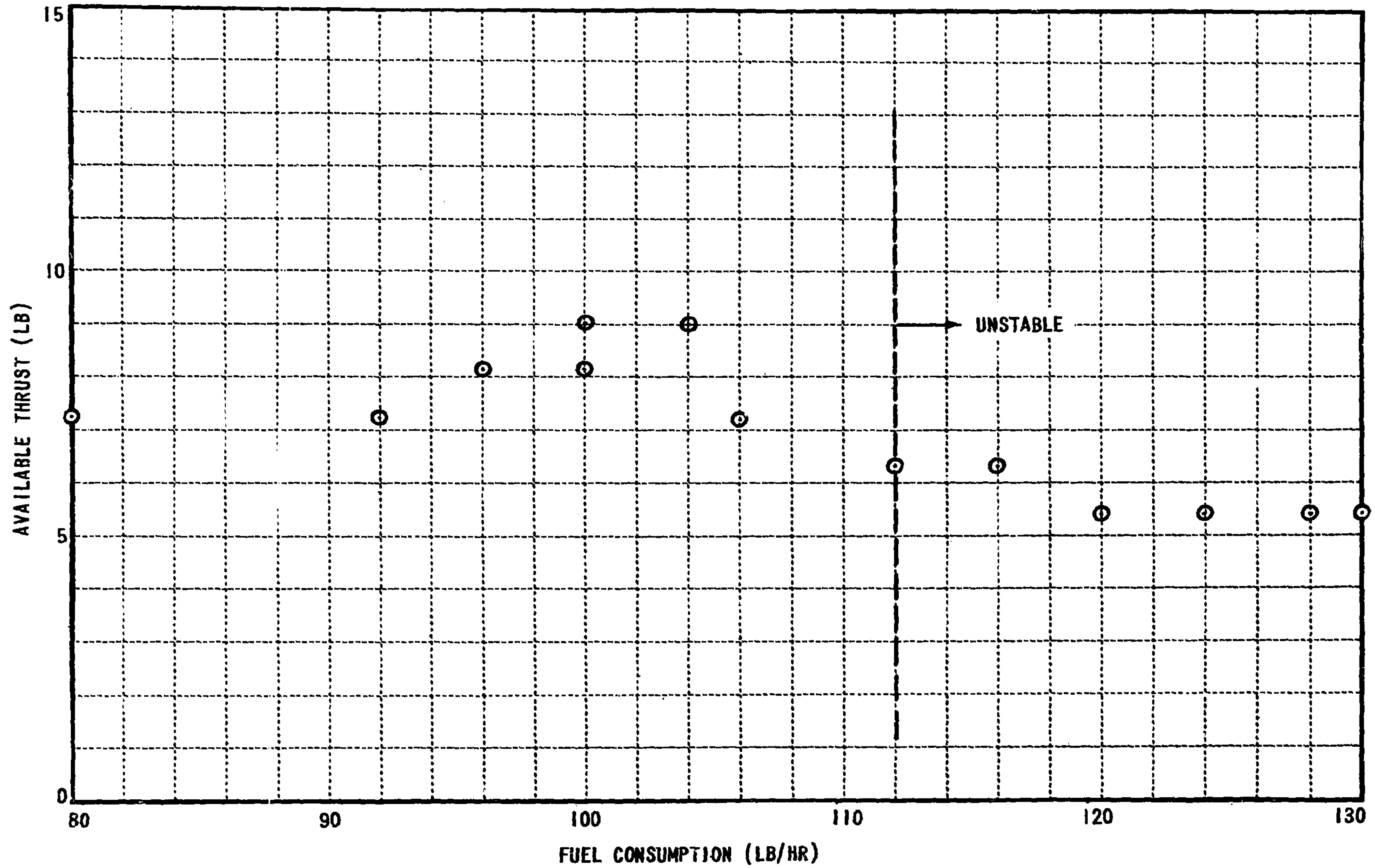

Figure 10

EFFECT OF INCREASING FUEL CONSUMPTION ON MAXIMUM THRUST OF $5\frac{1}{2}$" DIA VALVELESS PULSEJET (TIP SPEED 400 FPS)

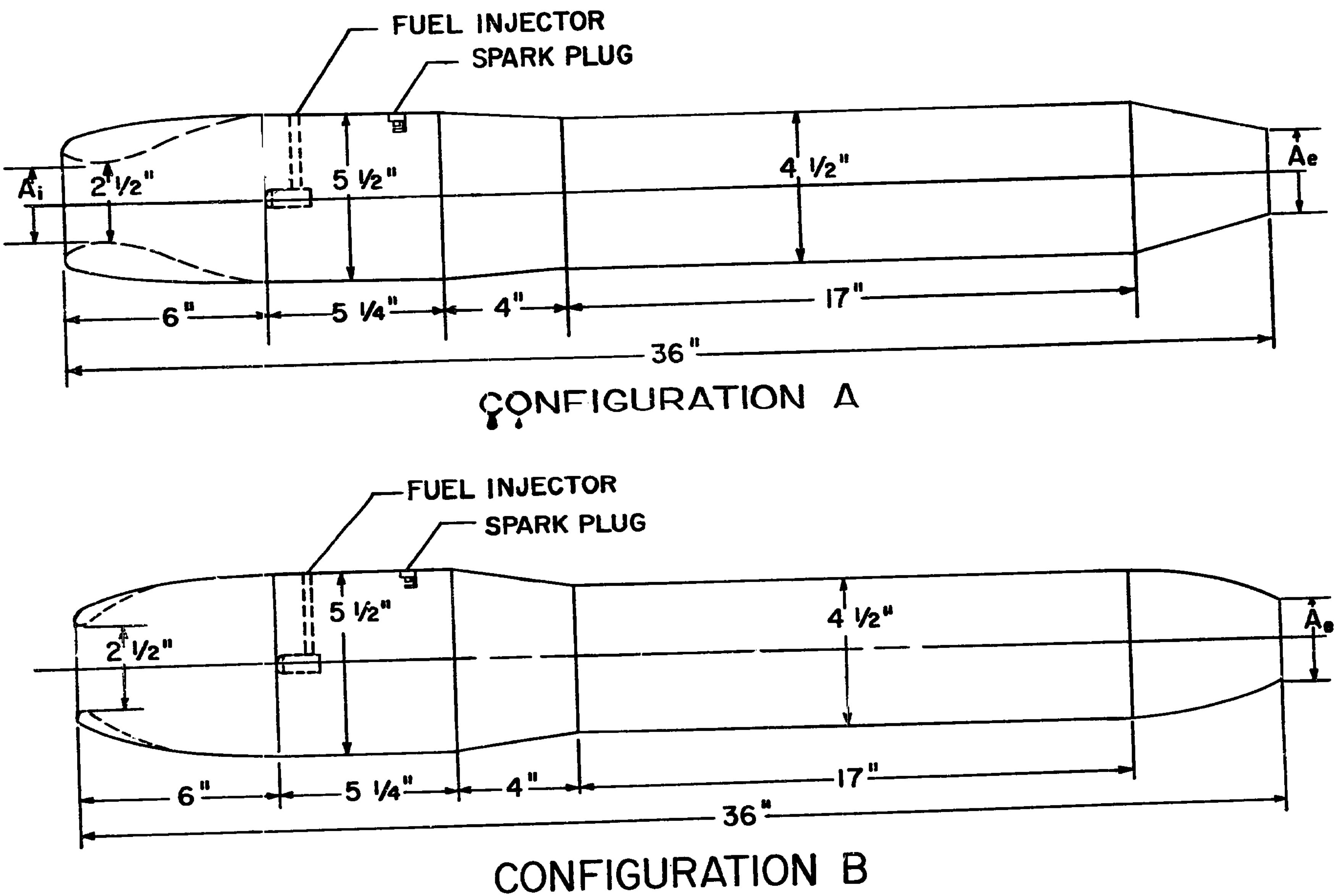

Figure 11
VALVELESS PULSE JET CONFIGURATIONS

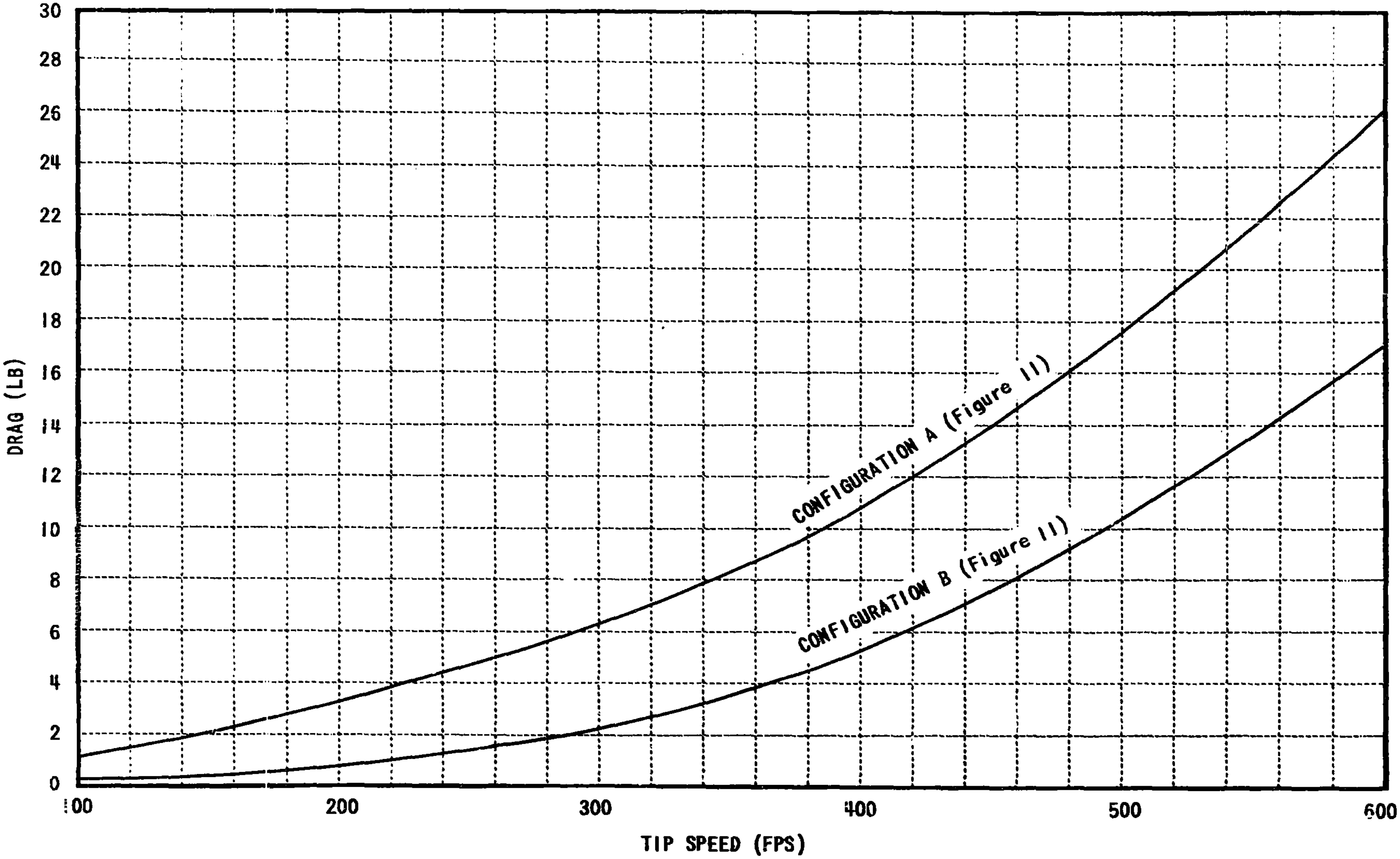

Figure 12

$5\frac{1}{2}$" DIS VALVELESS PULSEJET DRAG COMPARISON

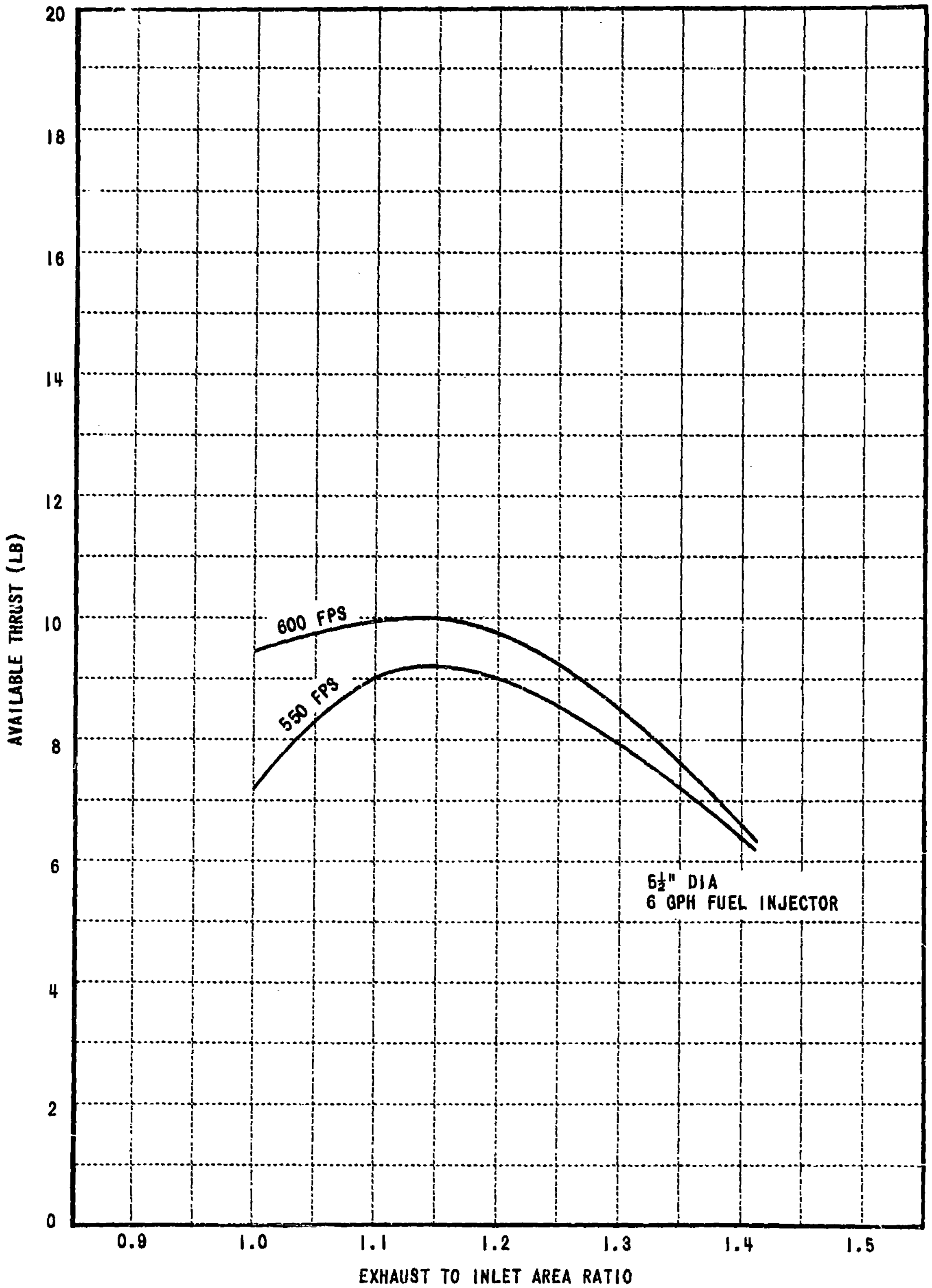

Figure 13

EFFECT OF AREA RATIO ON MAXIMUM AVAILABLE THRUST
OF VALVELESS PULSEJET CONFIGURATION B

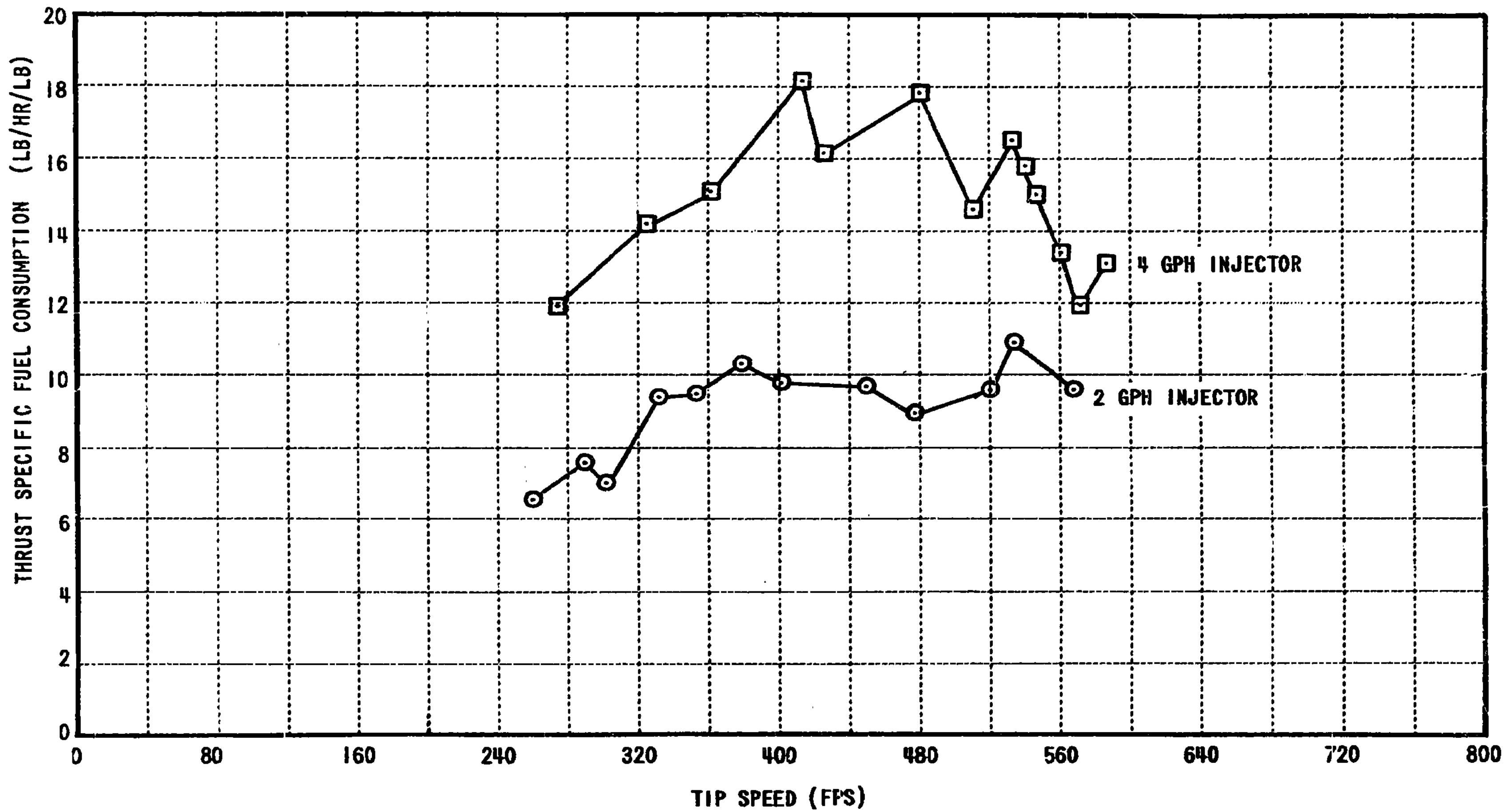

Figure 14

EFFECT OF FUEL INJECTOR SIZE ON PERFORMANCE OF VALVELESS PULSEJET CONFIGURATION B WITH AN AREA RATIO OF 1.0

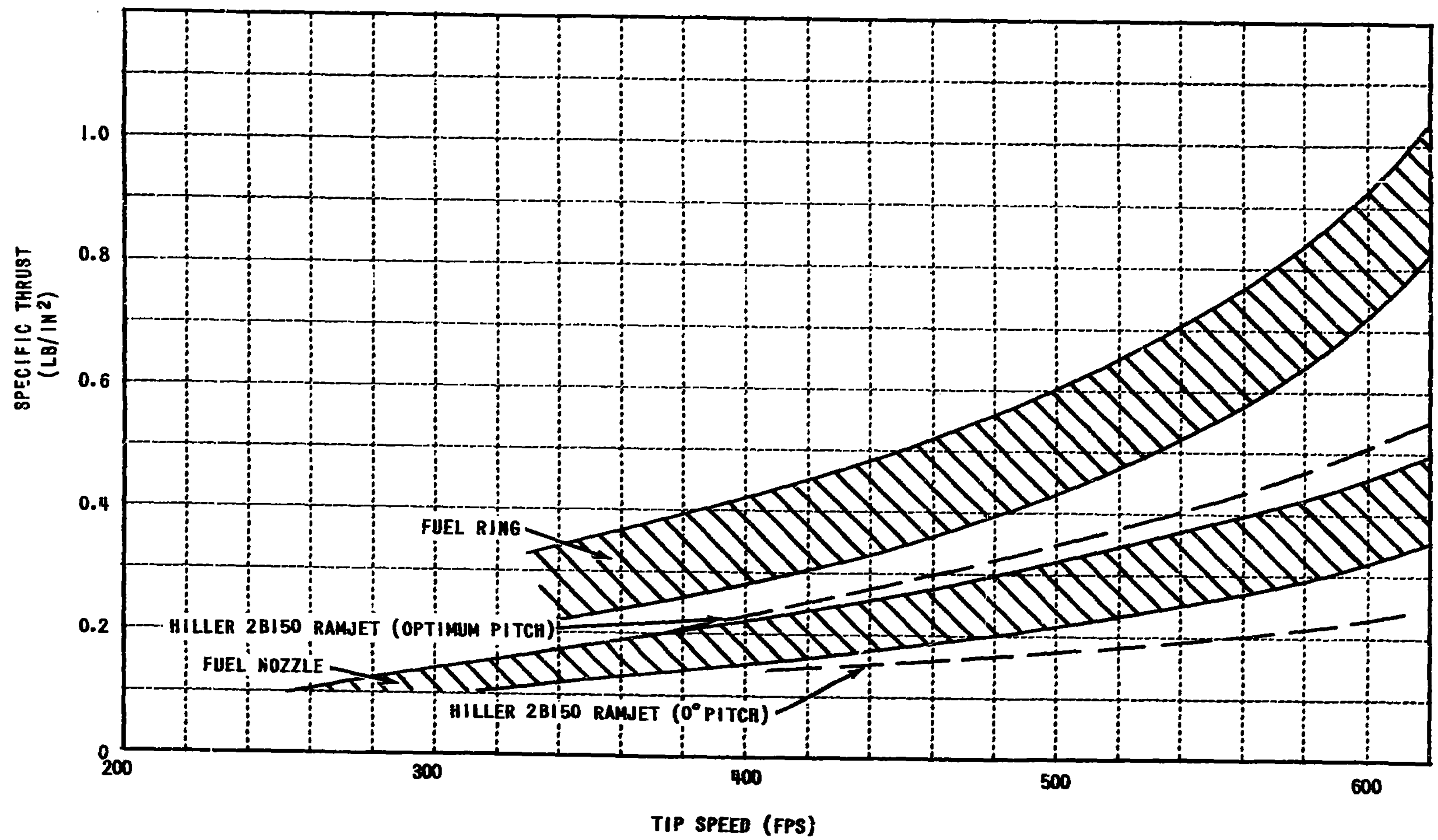

FIGURE 15

PERFORMANCE OF THE SUBSONIC RAMJET AND THE $5\frac{1}{2}$" DIAMETER VALVELESS PULSEJET AT 0° PITCH

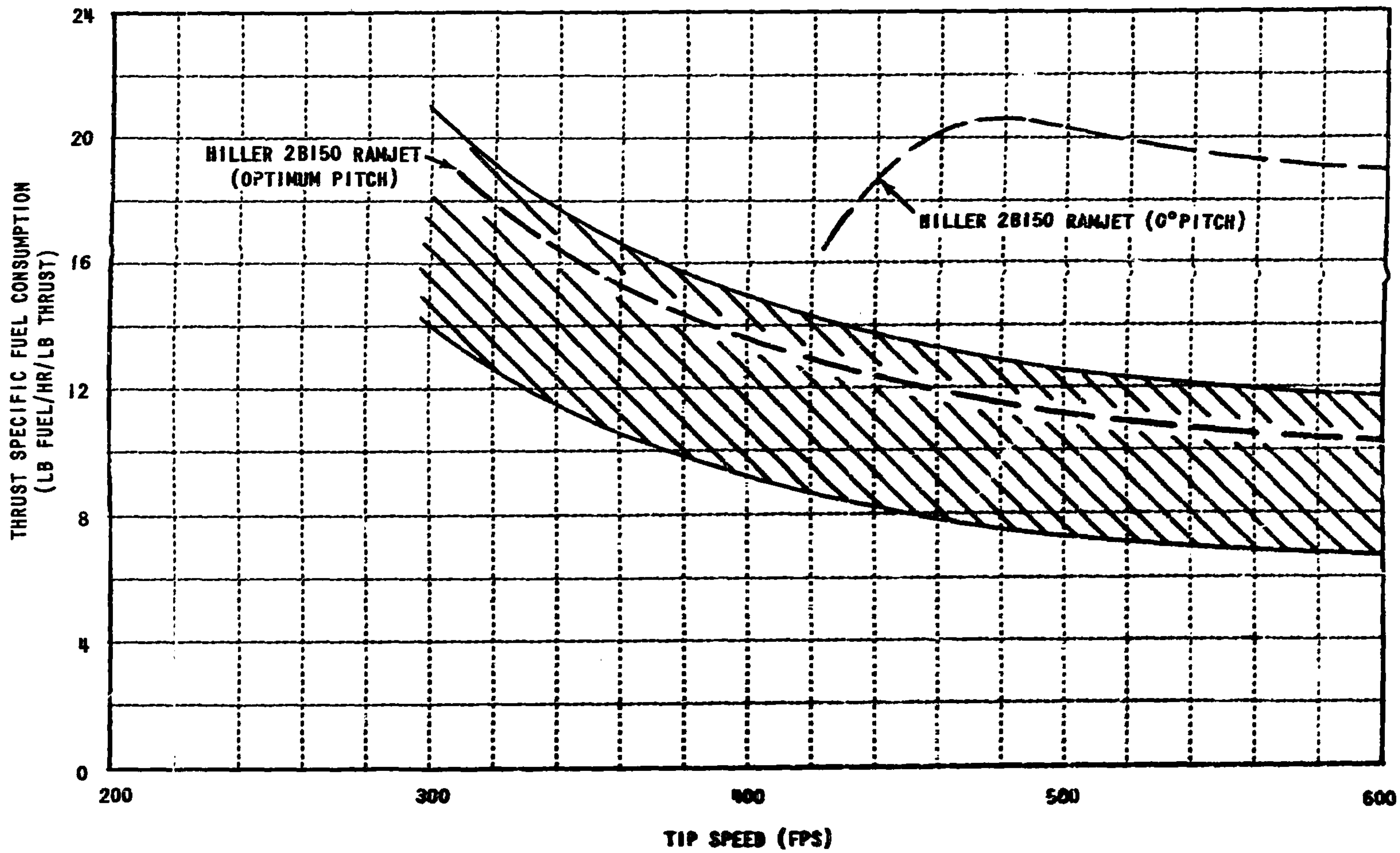

FIGURE 16

PERFORMANCE COMPARISON OF SUBSONIC RAMJET AND $5\frac{1}{2}''$ DIAMETER VALVELESS PULSEJET AT 0° PITCH.